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Ultrasonic Convergence Measurements

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UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

°C	degree Celsius	in	inch
ft	foot	m/s	meter per second
ft/°C	foot per degree Celsius	pct	percent
ft/min	foot per minute	pct/°C	percent per degree Celsius
ft/s	foot per second	psi	pound per square inch
ft/s·°C	foot per second per degree Celsius	s	second

ULTRASONIC CONVERGENCE MEASUREMENTS

By James R. McVey [1]

ABSTRACT

Tests during pillar robbing, longwall operations, and other mining activities indicate that roof-floor convergence rates can be used as an indicator of imminent roof failure. A large number of electrical-mechanical devices have been built to measure convergence as well as convergence rates, but most obstruct mine traffic and are costly and time consuming to install. The Bureau of Mines has designed and is evaluating three types of small ultrasonic units to make these measurements. The new instruments provide nonobstructing measurements up to 35 ft away. The ultrasonic transducers can be attached to a roof bolt, placed in an unsupported area (by means of a toss basket), or handheld. Total distance to the target and rate of closure are displayed digitally to 0.001 ft and 0.01 ft/min, respectively.

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INTRODUCTION

The Bureau has designed an experimental ultrasonic distance-measuring device using the Polaroid[2] sonar-camera focusing system. The instrument provides a nonobstructing means of measuring roof-floor convergence and convergence rates. Rates of closure are useful in ground control applications such as pillar robbing and longwall operations, and in places where detection of ground movements is critical to mine operations and safety of personnel.

Tests during retreat mining (pillar robbing), longwall mining, and other mining activities indicate that convergence rate (how fast the roof is moving) can be an indicator of imminent roof failure. The major problem in bad roof conditions is knowing that the roof is actually moving. Devices inserted in the roof can produce error in measurement because the roof may be separating at some location other than the area being measured.

Roof-to-floor measurements are usually a better indicator, unless floor heave is a problem.

A large number of electrical-mechanical devices have been built to measure convergence as well as convergence rates, but most obstruct mine traffic and are costly and time consuming to install. By request from the mining industry, the Bureau began a research program to build a rate-of-closure device in the fall of 1980. A mechanical closure-rate device was built and tested in June 1981.[3]

The availability of the experimental sonar kit from Polaroid provided an economical means of building the ultrasonic instrument. The transducer assembly costs approximately half the price of the potentiometer used in the mechanical extensometer. Three types of experimental instruments have been assembled, which are described in this report.

CONVERGENCE INSTRUMENTS

A small handheld instrument (fig. 1) was developed as an underground surveying tool that provides distance measurements of up to 35 ft. The instrument provides 0.01-ft resolution with ±0.02-ft accuracy (±0.25-in) when temperature correction is applied.

A portable underground unit (fig. 2) provides both convergence and a rate of convergence in two separate readings that are displayed each measurement cycle. The first reading is the total distance between the transducer and the rock surface, followed 6 s later by the rate of closure in feet per minute. These points move relative to each other.

This unit provides a distance measurement between the transducer and a point up to 35 ft away with 0.001-ft resolution and a convergence rate with 0.01-ft/min resolution. Accuracies of up to ±0.002 ft have been achieved over short distances (up to 10 ft) when temperature corrections are made.

A third unit (fig. 3) provides the advantage of an alarm and alarm set point. The operator can preset an alarm function that, when activated, will provide an audible alarm and light to indicate the set point has been reached or exceeded.

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[2]Reference to specific products does not imply endorsement by the Bureau of Mines.

[3]McVey, J. R., and W. L. Howie. New Closure Rate Instrument for Retreat Mining Operations. Min. Eng. (N.Y.), v. 33, 1981, pp. 1699-1700.

All three units described carry a 6-month extendible experimental permit from the Mine Safety and Health Administration (MSHA). The units are battery-operated and must be recharged in fresh air. Solder in fuses protects the unit electrically and is a part of the intrinsic safety. Exact replacement type and size fuse must be used.

GENERAL OPERATION

The ultrasonic convergence instruments utilize a Polaroid sonar transducer and auto-ranging card[4] as a base for distance measurement. Added circuitry provides the driving mechanism for the Polaroid ranging card, timing, and displaying of the signal transmitted and received.

Figure 4 provides a simplified block diagram of the instrument operation. A trigger oscillator generates a signal-designated velocity-sending wave (VSW) that causes the transducer to transmit a signal every 6 s. This transmitted signal will be reflected back to the transducer by any suitable object in its path. The time of flight (TOF), which is the time required for the transmitted signal to reach the target and return, is accurately timed and converted into feet, and displayed digitally.

The rate of convergence is determined by comparing two distance measurements over a 6-s time interval and multiplying the change by 10. The product is the rate of change in feet per minute.

The basic instrument operation is illustrated in figure 4. Circuit U1

produces a square-wave trigger signal VSW every 6 s to cause the ranging card to activate the transducer. The TOF signal is developed from M- and X-log signals generated on the ranging board, and comes
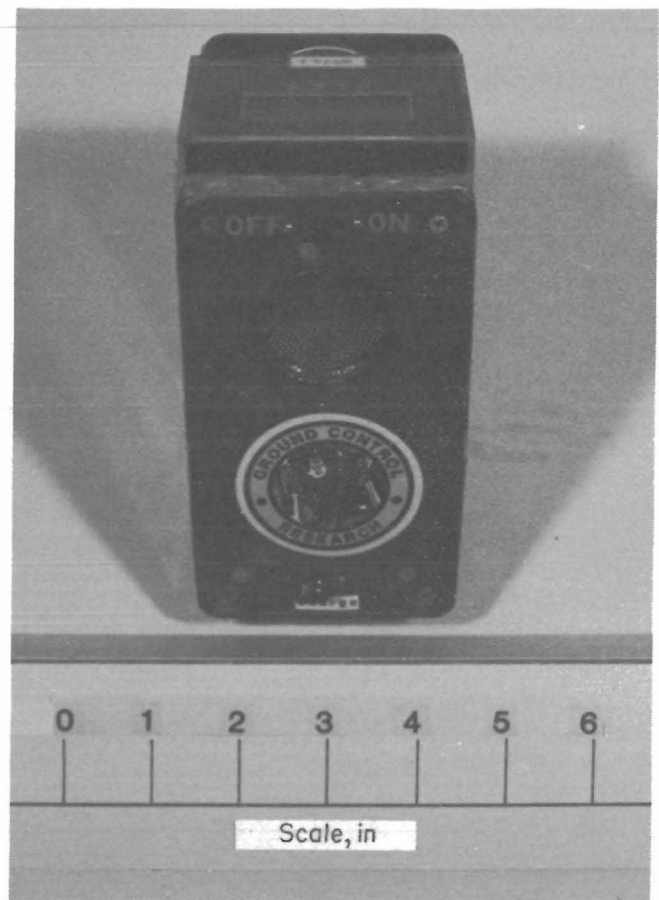

FIGURE 1. - Handheld instrument.

[4]Biber, C., S. Ellin, E. Shenk, and J. Stempeck. The Polaroid Ultrasonic Ranging System. Pres. at 67th Conv. (Audio Engineering Society), New York, Oct. 31-Nov. 3, 1980, 17 pp.; available from C. Biber, Polaroid Corp., Cambridge, MA.
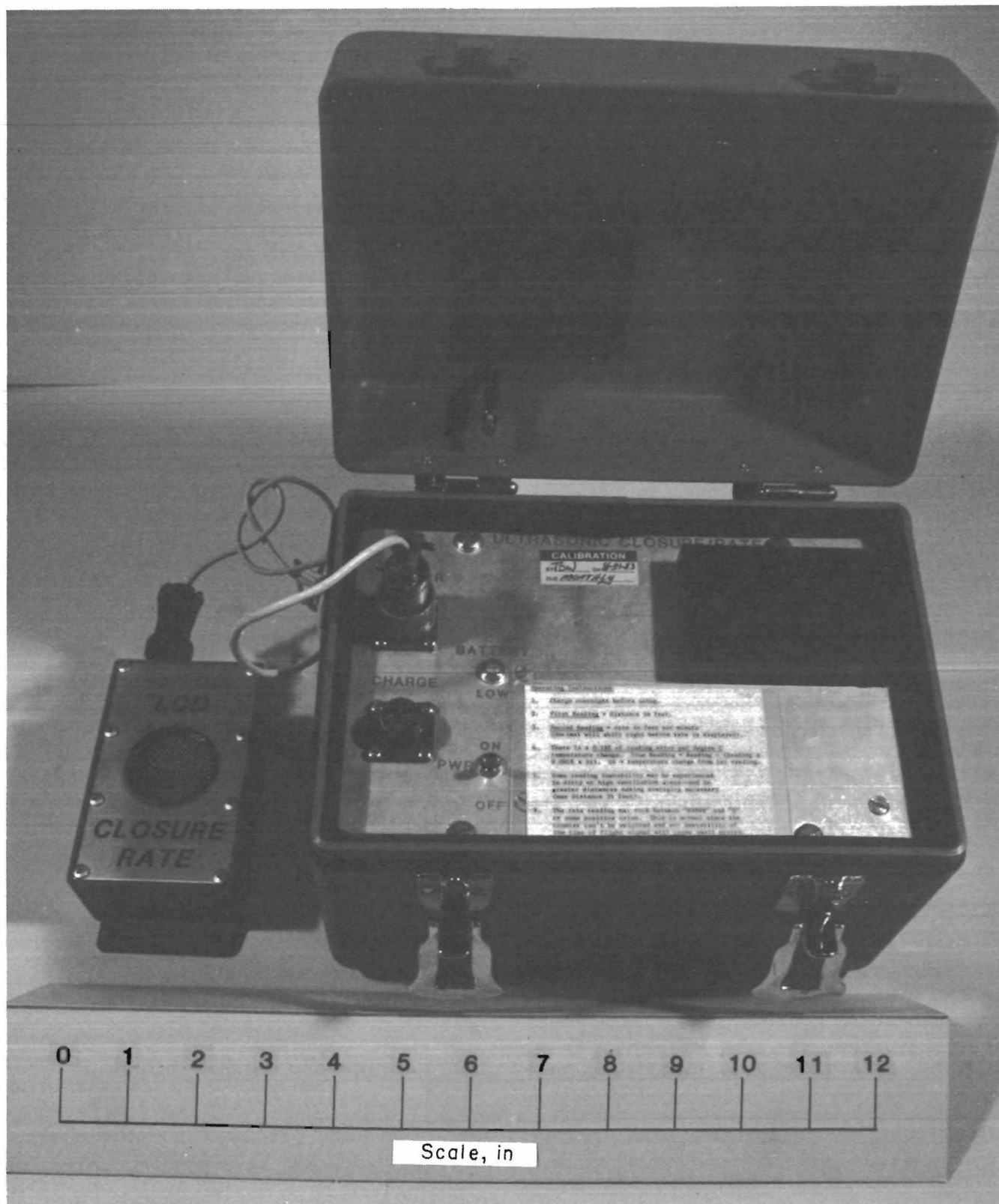
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FIGURE 2. - Portable underground unit.

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FIGURE 3. - Portable unit with alarm.

Ultrasonic
wave

U1 3-s trigger oscillator

6-s VSW

Polaroid ranging card

Transducer

U5 Up-down control and counter reset

X-log   M-log

TOF generator

U4 Main oscillator

Down
Up

U3 Counter control gate
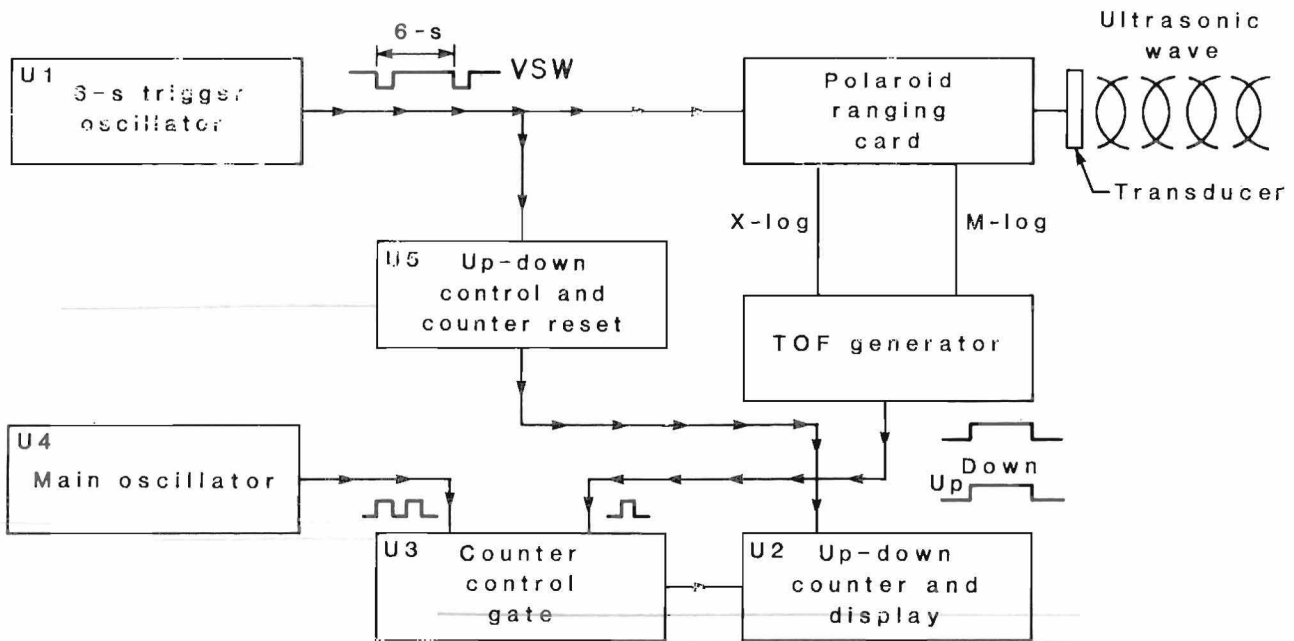
U2 Up-down counter and display

FIGURE 4. - Instrument operation block diagram.

from added circuitry attached to the board. This TOF signal is sent to the counter control gate, U3, to gate the counter on and off. The main oscillator, running at a calibrated frequency, is gated into the up-down counter. The gate time is determined by the width of TOF, which is representative of the distance being measured. The transmit signal X-log sets the leading edge of TOF. The reflected return wave (M-log) sets the trailing edge. The time duration between the two determines the width of the TOF pulse. The up-down counter, therefore, counts for the length of time it takes for the ultrasonic signal to make a round trip.

The counter counts up on the first U1 trigger and counts down 6 s later on the second trigger. The counter is reset after the countdown is displayed, starting a new cycle. The countup is displayed at the beginning of the 6-s cycle, and represents the total distance.

Any difference in count is displayed in the second reading (countdown). The decimal point is then shifted one place to the right on the second reading to give a multiplication factor of 10. The 6-s interval times a factor of 10 gives a conversion factor of feet per minute for the rate of convergence.

PROBABLE CAUSES FOR ERROR

The ultrasonic instruments can provide relatively good accuracy if care is taken in their use. Errors can occur from (1) dust in the air, (2) high air movement, (3) changes in temperature, and (4) shock waves and vibration caused by blasting or heavy equipment.

Excess dirt, coal dust, etc., which can cause reading errors, can be gently removed by tapping the transducer against one's hand, or by blowing it off with low-pressure compressed air (<15 psi), holding the air nozzle at least 5 in from the transducer. A vacuum can also be used as long as the nozzle covers <50 pct of the transducer grill. Dirty units can be cleaned with water or electric contact cleaner. Barometric pressure and humidity provide small errors and are not considered to be significant.

Temperature causes the most significant error in day-to-day readings. Figure 5 illustrates the increase in the velocity of sound through the air because of an increase in temperature. Because the air is less dense, less absorption takes place, causing an increase in velocity.

Temperature corrections must be made if the greatest accuracy is to be achieved. At 0° C, the velocity of the ultrasonic wave is 1,087.65 ft/s (331.5 m/s). At 21.5° C, the ultrasonic wave is traveling at 1,130.43 ft/s (344.5 m/s), an increase of 42.8 ft/s (12.3 m/s). Significant error can be induced in readings taken in the mine at one temperature with an instrument calibrated outside the mine at another temperature, unless a temperature

correction is made. Further calculations indicate that a 1° C change in temperature produces 0.18 pct (0.0018 × reading) error, which must be added to the reading for an increase in temperature and subtracted from the reading for a temperature less than the temperature at which the instrument was originally calibrated. The correction would be approximately 0.011 ft/°C at a distance of 6 ft.

If the user is to maximize instrument accuracy, measurement temperatures must be recorded at the time the measurement is made. Each instrument has the temperature at which it was calibrated recorded on the calibration sticker attached to the instrument. A temperature correction chart is supplied with each instrument.

INSTRUMENT USE AND CALIBRATION

Each instrument is designed for easy use. The transducer is pointed to the target, and the distance is displayed

directly in feet. If accurate distances are required, the transducer must be placed on a solid base. Accuracies on
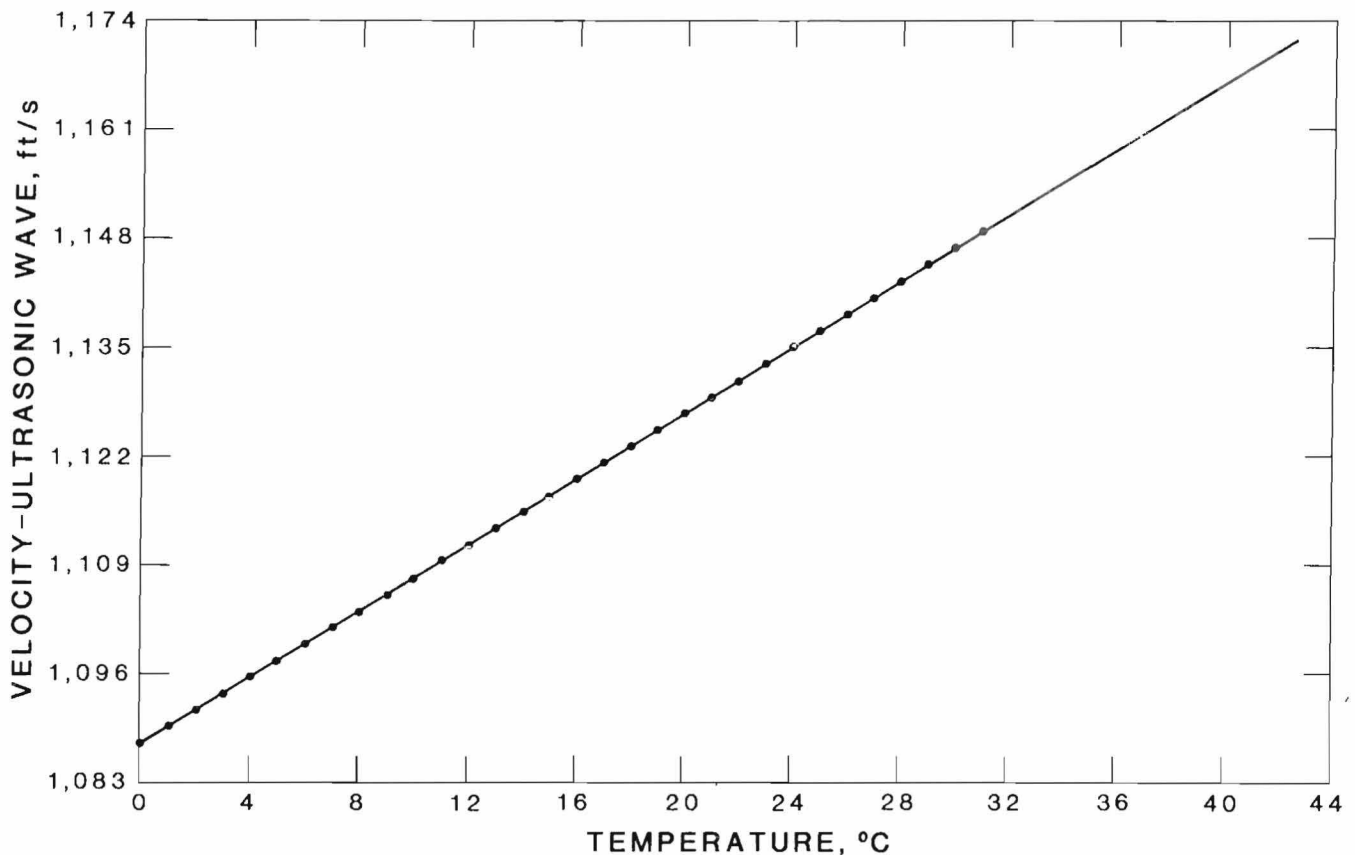

FIGURE 5. - Increase of velocity with temperature.

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the order of 0.002 ft would require something more substantial than loose soil or rock and no vibration. The distance measurement is made from the front edge (transducer surface) of the instrument to the target.

Each rate unit is supplied with an extra transducer, roof-bolt attachment, floor reference plate, and toss basket for measurements in the gob and other unsupported or dangerous areas. The floor plate allows the user a small, heavy reference base for floor-to-roof measurements. The bolt adapter allows attaching the transducer to roof bolts. The toss basket can be retrieved by pulling it out of an unsupported area by the transducer electrical cable. Two cables are provided, a 100-ft cable for long-distance remote measurements, and a short 10-ft cable for local measurements.

The small handheld distance-measuring unit (fig. 1) can be calibrated in the field, but the rate (dual-reading) units must be returned to the Bureau for calibration. The handheld unit is calibrated by removing the calibration label and locating the calibration adjustment. A target is set up, and 20.00 ft is measured accurately between the target and the leading edge of the instrument. The calibration screw is adjusted until an exact 20.00 ft is displayed in the readout. The temperature is recorded on a
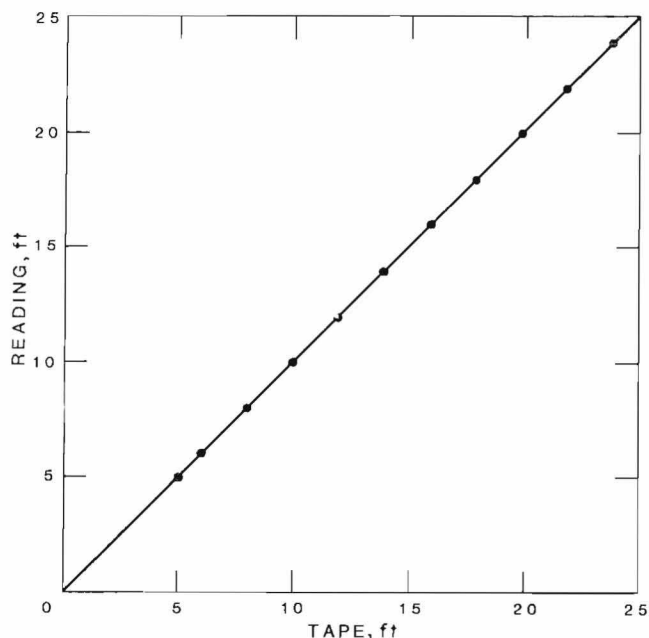

FIGURE 6. - Calibration plot.

new calibration label, and the new label is placed on the instrument over the adjustment.

In the laboratory, each ultrasonic instrument is calibrated through the use of a precision steel tape and target system. The instrument is checked at 2-ft intervals between 6 and 24 ft, and at 0.1-ft increments either side of each measurement. A linear regression calibration is used (fig. 6). The standard deviation of a single point is 0.003 ft or 0.036 in.

FIELD TESTS

Most tests have been run under controlled conditions in the laboratory, but field tests have been started. Although the field tests are not yet complete, some information has been compiled from two tests underground, one in salt and the other in an oil shale mine. Both mines have high backs (roofs) of over 20 ft. In both cases, some instability in readings was observed. Most large errors could be traced to heavy equipment vibrations and/or temperature variations. It is difficult to determine the cause of small variations, although it is suspected that changes in ventilation may be one reason.

Table 1 is a partial listing of readings taken in the salt mine. The range of error for this set was only 0.005 ft (0.060 in). The average reading was 20.199 ft. The distance is 20.199±0.0025 ft (±0.030 in). The tape-measured distance was 20.573 ft. The calibration factor (laboratory calibration) of 1.0187 × 20.199 ft gives a corrected reading of 20.577 ft. The difference between the tape and ultrasonic measurements is 0.004 ft (0.048 in). These tests, and those conducted in the laboratory, show real promise for most ground control measurement problems.

TABLE 1. - Field test data,[1] normal
(no corrections)

Reading	Distance, ft	Reading	Distance, ft
1	20.200	23	20.198
2	20.198	24	20.198
3	20.199	25	20.198
4	20.197	26	20.199
5	20.198	27	20.199
6	20.199	28	20.199
7	20.200	29	20.200
8	20.196	30	20.200
9	20.199	31	20.200
10	20.198	32	20.199
11	[2]20.208	33	20.201
12	20.199	34	20.199
13	20.200	35	20.199
14	20.197	36	20.198
15	20.199	37	20.201
16	20.197	38	20.200
17	20.197	39	20.200
18	20.197	40	20.201
19	20.197	41	20.200
20	20.198	42	20.198
21	20.198	43	20.199
22	20.198	44	20.199

[1]Average reading = 20.199±0.0025 ft
(±0.030 in). Error bandwidth = 0.005 ft.
[2]Bad reading--cause unknown.

Controlled laboratory tests have provided accuracies exceeding ±0.020 in. in short-distance measurements. Figure 7 shows a plot and data points for the worst case uncorrected readings from a series of 6-ft measurements over a 19° to 26° C temperature range. Figure 8 is the companion temperature-corrected computer plot. Measurements and measurement accuracies of this kind are not practical in the mine and are not expected.

The ultrasonic instrument is not designed to measure creep (<0.050 in) or other small displacements. Its prime purpose is for ground conditions where larger changes occur as in pillar robbing, longwall mining, and other caving operations where the surrounding ground movements are significant (>0.5 in).
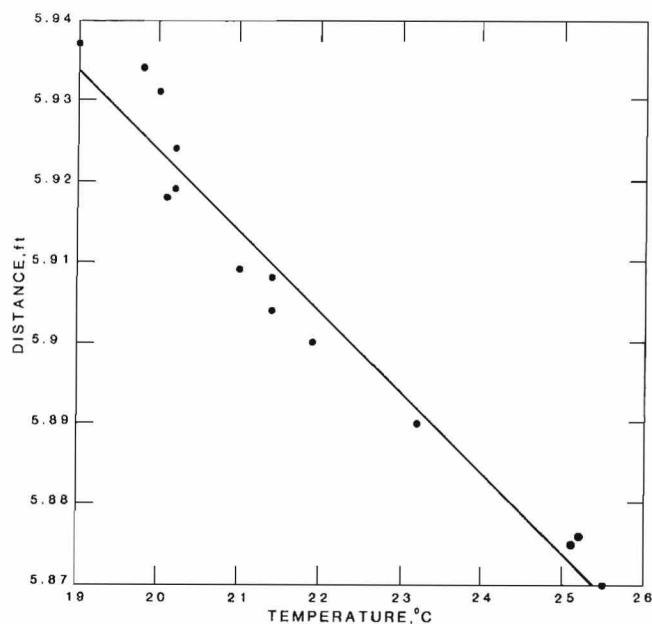

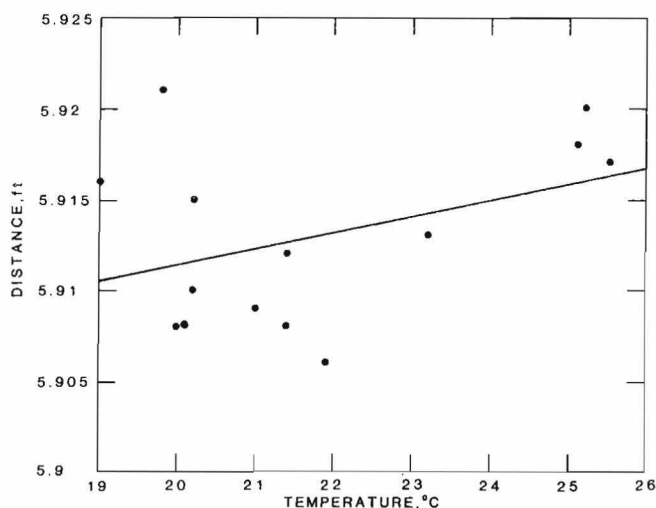FIGURE 7. - Worst case readings.

FIGURE 8. - Corrected readings.

Table 2 lists some worst case results taken from the field test at the oil shale mine. It is evident from the two sets of field data presented (tables 1-2) that the greater the distance to be measured, the more unstable the readings become. This is especially true in underground measurements. Laboratory tests are much more stable, but verify

TABLE 2. - Field data,[1] worst case

Reading	Distance, ft	Rate, ft/min	Reading	Distance, ft	Rate, ft/min
1	25.046	0.0	14	25.040	0.0
2	25.038	.0	15	25.056	.0
3	25.054	.0	16	[2]25.230	11.97
4	25.060	.0	17	25.045	.0
5	25.067	.0	18	25.054	.0
6	25.078	.0	19	25.046	.0
7	[2]25.222	11.43	20	25.023	.0
8	25.067	.0	21	25.040	.0
9	[2]25.225	11.35	22	25.033	.0
10	25.050	.0	23	25.051	.0
11	25.069	.0	24	25.048	.0
12	25.033	.0	25	25.021	.0
13	25.029	.0			

[1]Average reading = 25.046 ± 0.020 ft (±0.24 in).

[2]Large error caused by vibration of large vehicle. Rate indicates movement and represents Δ change $\times$ 10. Actual Δ distance changes are 0.143 ft, 0.135, and 0.197. These readings are invalid and should be ignored.

these findings. As discussed earlier, mine environment presents more cause for error.

Figure 9 illustrates the ultrasonic transducer's field of view. Any object or disturbance projecting into or entering the field will create a reflection, disturbing the measurement. Target or transducer movement, shock waves, etc., are prime suspects when large-scale errors are produced. Example results of such disturbances are illustrated in table 2.

Accurate measurements to the equipment limits require small targets attached to the reflecting surface. Sluffing pillars or a very rough roof can create errors. The ultrasonic transducer should be placed on a solid base and should either not be moved between readings or have a point of reference that is repeatable. Figures 10, 11, and 12 illustrate the use of transducer attachments.

ADDITIONAL VERIFICATION

MSHA approval, received at the time of this report, allowed tests to be scheduled for coal mine operations from September 1983 through September 1984.

Tests will be made in most types of coal mining operations, including pillar robbing, longwall mining, and conventional pillaring. Tests in metal and nonmetal
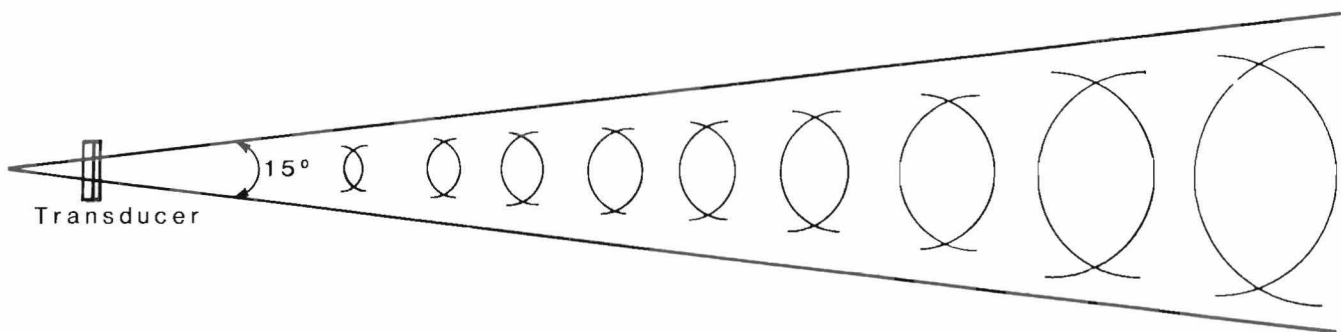

FIGURE 9. - Transducer field of view.

mines will continue. The prime purpose is to provide the industry with an economical nonobstructing means of determining convergence and rates of convergence for detecting and predicting hazardous roof conditions.

CONCLUSIONS

Thus far, ultrasonic convergence measurements have been proven acceptable in the laboratory and underground. Ultrasonics appears to be a viable means of measurement. Three types of instruments have been assembled, each having a specific application. Large-scale measurements from 1 to 35 ft, where changes of at least 0.5 in are expected, can be made, but measurement changes of <0.050 in cannot. These larger ground movements occur in most mining operations. This type of instrument should be especially effective in convergence measurements during longwall, pillar robbing, and other operations producing the larger ground movements.

Tests will be run in six coal and metal mines with different mining methods. The 1- to 35-ft measurement limitation does not appear to be a major problem. Tests in coal mines, where opening distances rarely exceed 12 ft, should have good results since accuracy and stability are much improved over these shorter distances. Additional information can be obtained from the author of this report.
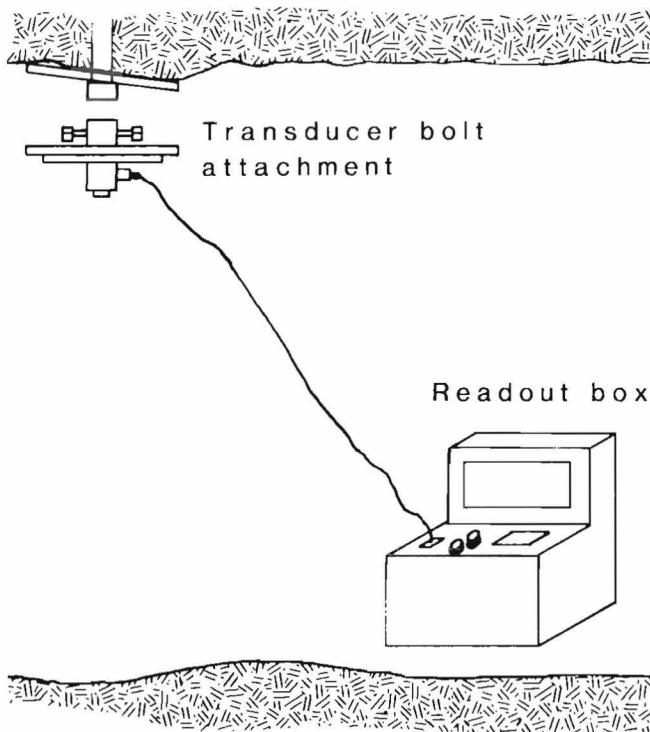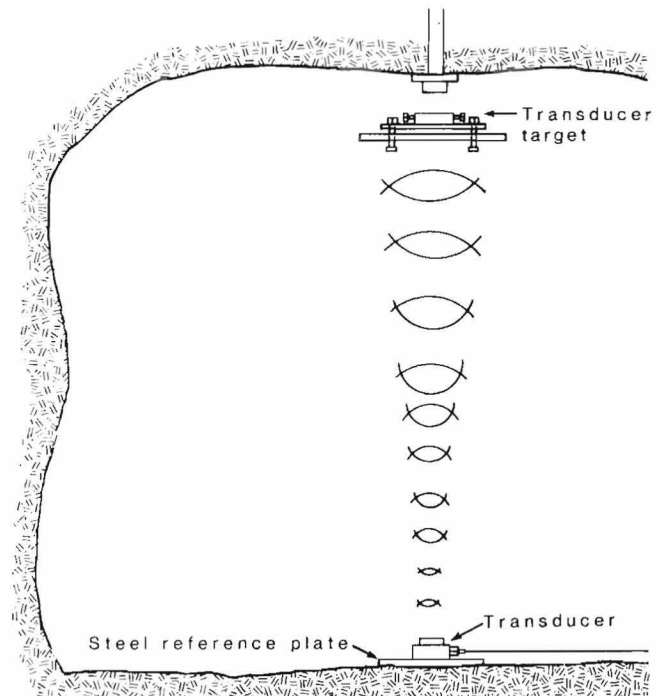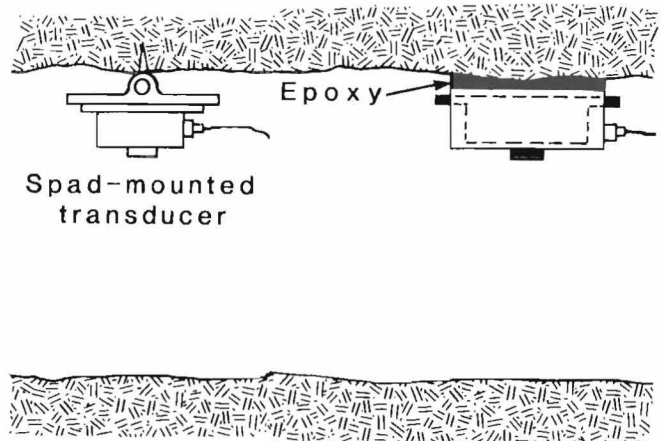

FIGURE 11. - Reference plate.

FIGURE 10. - Rock-bolt attachment.

FIGURE 12. - Roof mounting.